

# Combustion analysis for the 21<sup>st</sup> century

- NEO Monitors' TDLAS technology advances -  
Baseline-insensitive TDLAS with real-time source separation



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# NEO Monitors' TDLAS technology advances

## Baseline-insensitive TDLAS with real-time source separation

Gas analyzers based on tunable diode laser absorption spectroscopy (TDLAS) provide in-situ, contactless concentration measurements with high precision, high selectivity, and fast response. This, together with the low maintenance requirements and life-time calibration have made TDLAS the go to solution for industrial gas monitoring under harsh conditions, e.g. combustion processes. The progress in low-powered integrated circuits coupled with recent developments in digital signal processing algorithms are opening up new avenues for a more efficient use of the data collected by the analyzers. In this white paper we demonstrate the advances of our LaserGas™ III TDLAS analyzer and its advantages compared to conventional TDLAS systems. Our new LaserGas™ III Ultra analyzer features a novel baseline-insensitive measurement approach coupled with the next generation algorithm for disentangling multi-gas spectra in real time. We leverage these advances to widen the covered application-space to include longer optical path lengths with higher gas concentrations and more complex gas mixtures.

A TDLAS analyzer employs a single-mode semiconductor laser, a so called diode laser, whose output propagates through a gas while the wavelength is tuned across an absorption line of the gas component of interest. Since a diode laser typically emits a single color, i.e. its wavelength coverage is quite limited, conventional TDLAS analyzers typically target one gas per laser, as shown in Fig. 1(a). The absorption line is carefully selected such that it is well isolated from other lines to avoid interference from other gas components. This approach is referred to as 'single-line absorption spectroscopy'.

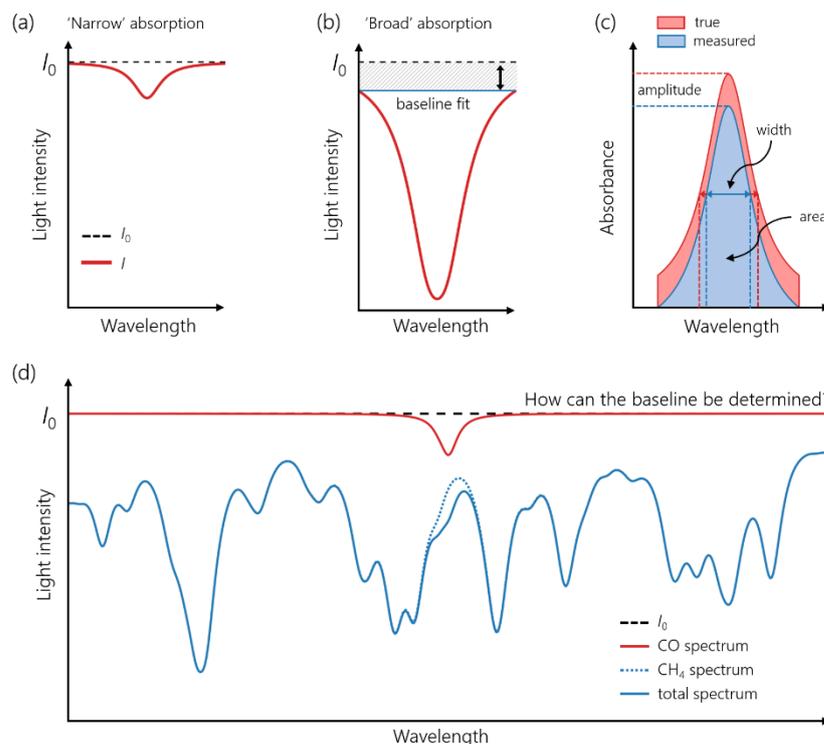
Based on first principles, a link between the transmitted laser intensity and the concentration of the absorbing gas component can be derived using the absorption equation (Beer-Lambert-Law):

$$I = I_0 e^{-\alpha(\lambda)}, \quad (1)$$

where  $I$  is the light intensity measured by the photodetector,  $I_0$  is the light intensity in the absence of absorbing gas (from now on referred to as the baseline) and  $\alpha(\lambda)$  is the absorbance of the target gas as a function of wavelength,  $\lambda$ . The gas concentration information is encoded in  $\alpha(\lambda)$  and can be retrieved using the gas pressure, temperature and optical path length.

It is clear from eq. (1) that in order to convert the transmitted light intensity into absorbance,  $\alpha(\lambda)$ , the baseline has to be known. The procedure of determining the baseline  $I_0$  and calculating  $I/I_0$  is commonly referred to as 'normalization'. After normalization, the concentration of the gas can be accessed through the area under the absorption line  $\alpha(\lambda)$ . The area can be determined directly by integrating  $\alpha(\lambda)$ , by fitting a spectroscopic model to  $\alpha(\lambda)$ , or fitting the model directly to the transmitted light  $I$  according to eq. (1). In all these cases the baseline  $I_0$  must be accurately determined to avoid errors in the resulting concentration. For a typical TDLAS application where the measured absorbance is around 0.05, achieving a 2 % error in the absorbance requires reaching an error on the baseline of only 0.1 %. The method of detection described above is commonly used in traditional TDLAS analyzers based on direct absorption spectroscopy (DAS).

**Fig. 1. Direct absorption spectroscopy.** (a) 'narrow' absorbing line with possibility of performing a baseline fit. (b) 'Broad' absorbing line where there is no part of the spectrum that can be used to determine the baseline for normalization. (c) The effects of incorrect baseline assessment. Red area corresponds to the true absorbance and blue to the measured. In general, the concentration will be underestimated. (d) Example of when baseline fitting breaks down due to the lack of non-absorbing region to infer the baseline.



The baseline  $I_0$  can in principle be found by collecting a reference measurement free from absorbing gas (zero-gas). However, such an approach is not feasible for in-situ measurements, where the baseline varies rapidly in amplitude and shape due to dust, turbulence and mechanical vibrations. Therefore, the standard approach for in-situ measurements is to estimate the baseline by fitting a polynomial (or other function) to the measured transmitted intensity using spectral regions that are free from absorption. However, if the absorption is broad due to a high concentration of the absorbing gas or due to a high gas pressure, the wings of the absorption line may extend far outside the scanned region so that no accessible regions are free from absorption. This is illustrated in Fig. 1(b), where the baseline found by the polynomial fit differs noticeably from the true baseline. Incorrect determination of the baseline directly affects the measured absorbance  $\alpha(\lambda)$ , as is shown schematically in Fig. 1(c). This inevitably propagates to errors in measured concentrations whether they are obtained from direct integration of the profile or from a fit using a spectroscopic model. In addition, many gases exhibit quite complex absorption spectra where the closely spaced lines are partly overlapping. In this case, determination of the true baseline by fitting becomes virtually impossible. Such an example is shown in Fig. 1(d) where a signal from carbon monoxide is hidden in a large background of methane. It is clear that in order to handle applications where such effects can occur, the instrument cannot rely on traditional baseline fitting.

Our novel 'baseline-insensitive' approach uses a set of carefully chosen digital filters that preserve the characteristics of the absorption features while efficiently filtering out the baseline term. A physical model can be constructed for the filtered signal to retrieve the spectroscopic parameters needed to calculate the gas concentration, analogous to what is done in traditional DAS when the gas concentration is calculated using a spectroscopic model for  $\alpha(\lambda)$ .

This 'baseline-insensitive' approach removes the need for the normalization step including baseline fitting and makes the detected absorption signal insensitive to transmission fluctuations and to baseline variations due to background absorption. An additional benefit is an added capability to perform accurate measurements in the regime of large optical depth, i.e. strong absorption, where the light intensity over the entire laser scan is heavily attenuated by absorption, thereby enabling applications with significant contributions from background gas components.

The table below highlights the benefits of our new approach compared to traditional TDLAS.

Conventional TDLAS systems:

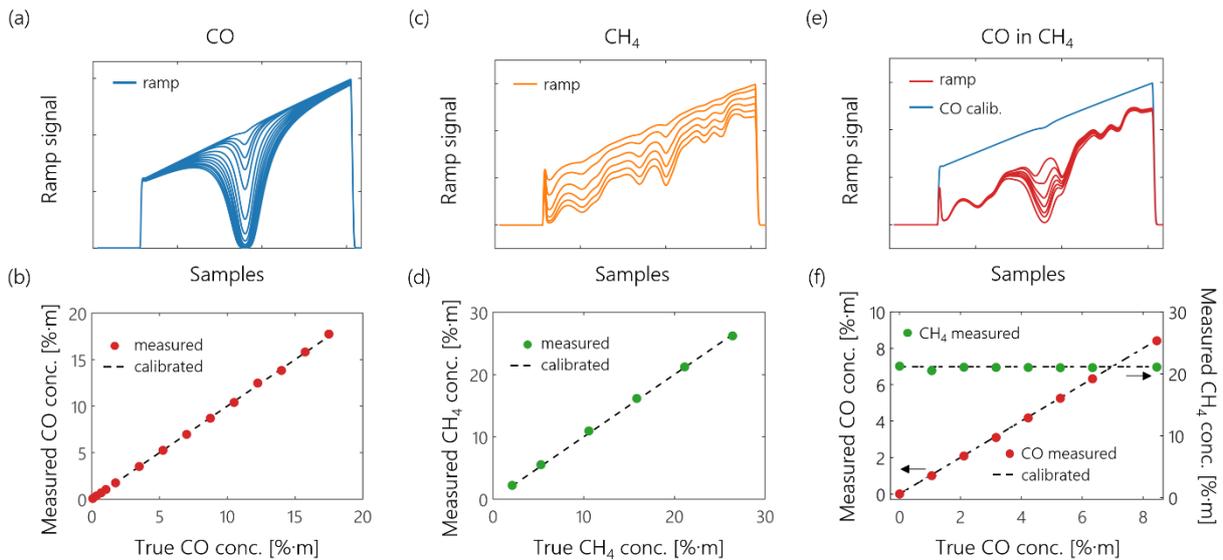
- Baseline polynomial fit
- Normalization required
- Limited to spectral regions and absorption levels where the baseline can be found
- From  $10^4$  to  $10^5$  dynamic range

TDLAS by NEO Monitors:

- Baseline-insensitive
- No normalization needed
- Linear response up to 100 % absorption, even if the baseline is not accessible
- More than  $10^6$  dynamic range<sup>1</sup>

To demonstrate how this works in practice let us consider an industrial process heater/furnace application where a TDLAS analyzer is tasked with monitoring CO and CH<sub>4</sub>, where low concentrations are typically used to control the process and high concentrations for triggering safety functions. Since both CO and CH<sub>4</sub> absorbs in the spectral region around 2.3  $\mu\text{m}$ , this wavelength is a natural choice. However, the application is challenging since the absorption spectra of CH<sub>4</sub> and H<sub>2</sub>O are relatively dense at this wavelength, which makes it difficult to find lines of CO free from CH<sub>4</sub> and H<sub>2</sub>O interference and in addition suitable for high temperature measurements. In practice, a wavelength region with minimum interference from H<sub>2</sub>O rather than CH<sub>4</sub> must be chosen. There is a huge variety of process heaters across different industries, ranging from 1-2 meters in diameter in pilot plants, up to 20-27 meters in refineries. The ranges typically required to control combustion and detect potentially unsafe operation are 0-1 % for CO and 0-5 % for CH<sub>4</sub>. For one meter of optical pathlength, the corresponding absorption at 2.3  $\mu\text{m}$  is not strong. However, since the absorbance is proportional to the pathlength, for a 20 meter heater the effective path-integrated concentration ranges become 20 %-m for CO and to 100 %-m for CH<sub>4</sub>. This requires an analyzer that is capable of measuring absorption in the regime of large optical depth. In general, the path-integrated concentration units %-m and ppm-m are convenient to use in cases of very long optical pathlengths, such as those found in open path (OP) gas monitoring applications. These units can also be useful for combustion safety monitoring of large process heaters. Let's take an example of a large process heater of 20 meters. A CH<sub>4</sub> readout of e.g. 2 %-m may indicate the formation of a potentially dangerous gas cloud, 1-meter in size with 2 % CH<sub>4</sub>, or 4 % CH<sub>4</sub> in a 0.5 meter-sized cloud, which could indicate a possible burner failure. The same cloud given in the traditional % volume unit, i.e. averaged over the whole length of the heater, would result in a readout of only 0.1 % of CH<sub>4</sub>, and the potentially unsafe situation may remain unnoticed. A versatile TDLAS combustion analyzer must handle high dynamic ranges for CO and CH<sub>4</sub> and reliably be able to measure 1 % over 1 meter (1 %-m) as well as 1 % over 20 meters (20 %-m) with similar accuracy and good linearity. Figure 2 shows examples of absorption levels that can occur in this type of application. Figure 2(a) shows the spectra of path-integrated CO concentrations from a few thousand ppm-m up to 17.5 %-m and in Fig. 2(b), a linearity check for CO is provided. With a single point calibration, the analyzer is linear up to ~99.9 % of relative CO absorption. Figure 2(c) shows the corresponding measurements for CH<sub>4</sub>, here the analyzer measures up to 25 %-m with excellent linearity [see Fig. 2(d)]. Finally, Fig. 2(e) shows combined spectra, where the path-integrated concentration of CH<sub>4</sub> is kept constant at 21 %-m while the concentration of CO is varied from 0 to 8.5 %-m. Figure 2(f) shows that despite having no access to the baseline due to the large background absorption of CH<sub>4</sub>, the analyzer maintains its linearity for CO.

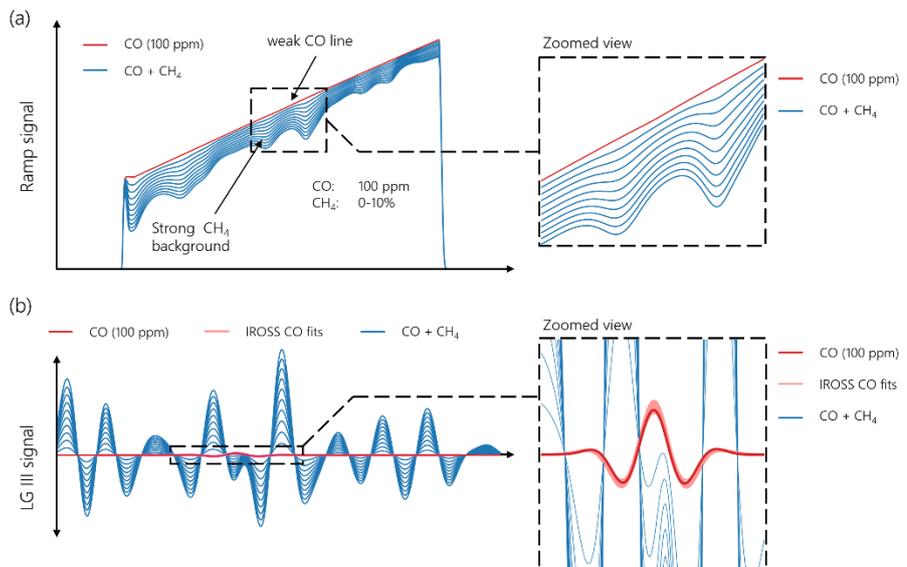
<sup>1</sup>Defined as the ratio of upper detection limit to the lower detection limit (LDL/precision). The dynamic range varies depending on wavelength region and application.



**Fig. 2. Furnace application.** (a) Varying concentrations of CO at atmospheric pressure. (b) Linearity validation measurement. The instrument shows a linear response to path integrated CO concentrations up to 17.5 %·m. (c) Varying concentrations of CH<sub>4</sub> at atmospheric pressure. (d) Linearity validation measurement. The instrument shows a linear response to path integrated CH<sub>4</sub> concentrations up to 25 %·m. (e) Varying concentrations of CO in a strong CH<sub>4</sub> background. (f) Despite the large CH<sub>4</sub> background (21 %·m), the instrument is able to measure CO up to 8.5 %·m.

Baseline-insensitivity is only one piece of the puzzle, in order to accurately measure CO in a background of CH<sub>4</sub> the analyzer needs to properly handle strongly interfering gas components, i.e. gases whose lines significantly overlap. The progress in processing power and advanced statistical algorithms over the last decades have opened up new possibilities for on-instrument, real-time, gas interference suppression [1]. We apply these modern tools in our proprietary framework called IROSS (in-situ real-time overlapping spectra separation). Our recent improvements of this framework are shown in Fig. 3. Stacked LaserGas™ III Ultra signals are shown for 100 ppm CO together with increasing concentrations of CH<sub>4</sub> spanning from zero (red trace, only CO) to 10 % (blue traces, CO + CH<sub>4</sub>). On the right side a zoomed view of the region around the CO line is shown. Strong absorption signals of CH<sub>4</sub> can be observed (blue traces) while the absorption signal for CO is too weak to be noticed (red trace). Figure 3(b) shows the corresponding signal after the digital filtering. On the right side a zoomed view of the region around the CO line is shown. The red trace corresponds to a measurement without CH<sub>4</sub> (0 %). The pink traces are the CO separated signals in presence of varying CH<sub>4</sub> (up to 10 %). As can be observed, the retrieved CO signals are virtually constant despite overlapping CH<sub>4</sub> absorptions up to two orders of magnitude stronger. This example demonstrates the capability of the analyzer to precisely measure ppm levels of CO in presence of % levels of CH<sub>4</sub>. Depending on the wavelength region and tuning range of the laser, three or four gas components can be separated using this approach.

**Fig. 3. Source separation using IROSS.** (a) Laser ramp signals with 100 ppm of CO and varying levels of CH<sub>4</sub> (0-10 %, blue traces). The red trace is obtained from a measurement of 100 ppm CO without CH<sub>4</sub>. To the right, zoomed view of (a) around the region with the CO line. (b) LaserGas™ III Ultra spectra. The blue trace are spectra with 100 ppm of CO together with varying levels of CH<sub>4</sub>. The red trace corresponds to 100 ppm of CO and the pink traces are estimated CO spectra given by IROSS. To the right, zoomed view of (b). Despite the large CH<sub>4</sub> background, the CO spectra are consistent.



## Conclusion

As the TDLAS technology continues to evolve from the traditional 'single laser – single gas' analyzers to the more challenging 'single laser – multi-gas' analyzers, advanced signal processing is playing a crucial role. Our new 'baseline-insensitive' LaserGas™ III Ultra signal processing developments remove the need for traditional baseline fitting and enable applications with large levels of absorption across the entire tuning range of the laser. In addition, we further developed our source separation algorithm to increase our ability to decouple signals from multiple gas components in real-time. Combined, these two developments enable handling of more complex gas compositions, higher concentration ranges and longer optical path lengths than ever before.

## References

1. P. Geiser, V. Avetisov, J. Wang, and L. Sieker, "Smart combustion analysis," Hydr. Carb. Eng. (2019).

## / About us

At NEO Monitors we are committed to helping our customers achieve optimum performance for their individual applications while never compromising on system reliability.

For decades, we have dedicated our business to the sole purpose of improving how our customers monitor and control gas and dust — you could even call it a devotion.

Both on the field and in the lab, we are constantly discovering new ways to deliver gas and dust analysis beyond what is believed to be possible.

Today, we are a leading manufacturer and supplier of TDLAS-based gas and dust analyzers for process optimization, emission monitoring and safety applications. Our analyzers can measure over 40 gases and combinations and are used in a wide range of applications in all kinds of industries. We have more than 40 distributors spread across all continents, a subsidiary in the US and a Sales office in China. It is the fastest growing European company in this niche, with over 18.000 analyzers installed.

Our dedication enables us to understand our customers' application needs and in turn, design high-performance products and solutions that meet the ever-changing demands facing industrial manufacturers around the world today — and tomorrow.

We don't believe in throwing around industry buzz words, or making claims we can't back up.

Ultimately, our intention is simple: to deliver the most accurate gas and dust measurement possible, while never compromising on system safety and reliability.

That's it.

We are, in other words: **Performance you can trust.**

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### NORWAY

**NEO Monitors AS**  
Prost Stabels vei 22

N-2019 Skedsmokorset, Norway

Switchboard +47 67 97 47 00  
Sales and application +47 400 01 613  
[neosales@neomonitors.com](mailto:neosales@neomonitors.com)  
[www.neomonitors.com](http://www.neomonitors.com)

### CHINA

*Sales & service:*

**NEO Monitors AS Shanghai Office**  
Tower A Room 2312  
Far East International Plaza  
319 Xianxia Road,  
Shanghai  
Phone: +86 (21) 5266 0501 /  
+86 (21) 5266 0503

*Non-commercial requests:*

**NEO Monitors AS Beijing Office**  
Lufthansa Center, C613A,  
50 Liangmaqiao Road,  
Beijing  
Phone +86 (10) 5830 2877  
[info@neomonitors.com.cn](mailto:info@neomonitors.com.cn)

### USA

**NEO Monitors Corp.**  
11200 Westheimer Rd, Suite 500  
Houston, TX 77042  
[us@neomonitors.com](http://us@neomonitors.com)